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X-ray spectra from convective photospheres of neutron stars

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Abstract. We present first results of modeling convective photospheres of neutron stars. We show that in photospheres composed of the light elements convection arises only at relatively low effective temperatures ($\lesssim 3-5\times 10^4$ K), whereas in the case of iron compositon it arises at $T_{\rm eff} \lesssim 3\times 10^5$ K. Convection changes the depth dependence of the photosphere temperature and the shapes of the emergent spectra. Thus, it should be taken into account for the proper interpretation of EUV/soft-X-ray observations of the thermal radiation from neutron stars.

1. Introduction

Recent ROSAT observations of pulsars revealed that some of them emit thermal-like radiation in the soft X-ray range (Ögelman 1995). These observations stimulated further investigations of neutron star (NS) photospheres responsible for the properties of the emitted radiation.

One of important and hitherto untouched problems associated with modeling of the NS photospheres is the problem of convective energy transport which can affect the temperature distribution and the emergent spectra. Due to huge gravitational accelerations, $\sim 10^{14}-10^{15}$ cm s^{-2}, the NS photospheres are much denser, $\rho\sim 0.001-1$ g cm^{-3}, than those of usual stars. The increased densities shift ionization equilibrium: the nonionized fraction grows with ρ at moderate densities, $\rho \lesssim 0.01-0.1$ g cm^{-3}, and sharply decreases at $\rho \gtrsim 0.1-1$ g cm^{-3} due to pressure ionization. As a result, zones of increased opacity (increased radiative gradient $\nabla_{\rm rad}$) and reduced adiabatic gradient $\nabla_{\rm ad}$ develop in the NS photospheres at temperatures much higher than in photospheres of usual stars, which may cause convective instability at depths where the emergent spectrum is formed. So far the NS photospheres have been considered either for stars with very strong surface magnetic fields $B\sim 10^{12}-10^{13}$ G (see, for example, Pavlov *et al.* 1994) where existing convection theories are not applicable, or for 'nonmagnetic' (low-field) photospheres, $B < 10^8-10^9$ G, with high surface effective temperatures $T_{\rm eff} > 10^{5.5}-10^6$ K (Romani 1987), where the convection can hardly be expected. Since thermal NS radiation can be detected for $T_{\rm eff} \gtrsim 2\times 10^5$ K in the soft X-ray range, and for even lower temeratures, $\gtrsim 2\times 10^4$ K, in the UV/optical range (Pavlov *et al.* 1995), the study of the convective NS photospheres is important for the proper interpretation of these observations.

The convective flow in stellar photospheres is turbulent and imposes many complicated problems. A common practice, which we follow here, is to use the phenomenological mixing-length theory with the traditional Schwarzschild criterion for convective instability, $\nabla_{\rm rad} > \nabla_{\rm ad}$. This theory has been widely implemented and testified.

Details of our numerical calculations will be described elsewhere. Generally, we employ the complete linearization method for computing the photosphere models and include the convective energy transfer as described by Mihalas (1978).

2. Results and Discussions

We calculated the model of nonmagnetic photospheres for different chemical compositions. Here we present examples for pure hydrogen, helium and iron compositions at the gravitational acceleration $g = 2.43\times 10^{14}$ cm s^{-2} which corresponds to standard NS mass $M = 1.4M_\odot$ and radius $R = 10$ km. The raditive opacities and equation of state for the iron composition were taken from the OPAL library (Iglesias *et al.* 1992). The results can be directly applicable to very old NSs with low magnetic fields (e. g., millisecond pulsars).

Our results show that, similar to the case of usual stellar photospheres, the convective energy transfer begins to play a role at lower surface temperatures when atoms are not fully ionized and the radiative opacities are strongly increased by contribution of the bound-free and bound-bound transitions. The increased opacities result in high values of $\nabla_{\rm rad}$ — the depth dependence of the temperature becomes steeper in order to transfer the energy flux throughout the photosphere. On the other hand, $\nabla_{\rm ad}$ in the dense partially ionized layers can be much smaller than its limiting value 0.4 for an ideal fully ionized or fully nonionized gas (see, for example, Cox and Guili 1968). As a result, superficial convection zones in NS photospheres arise and, as in usual stars, they are associated with layers of partial ionization. Our computations show that ∇_{ad} can drop down to $\simeq 0.1$ when the nonionized fractions are $\gtrsim 70\%$.

The actual temperature gradient ∇ in the convection zones satisfies the following relation: $\nabla_{ad} < \nabla < \nabla_{rad}$. Fig. 1 shows the temperature distributions in photospheres with and without allowance for convection. One can see that convection leads to more gradual profiles, in accordance with the above relation. Both in very surface layers, where ∇_{rad} is too low, and in deep layers, where ∇_{ad} is close to its maximum value, convection is absent, and the temperature profiles remain the same.

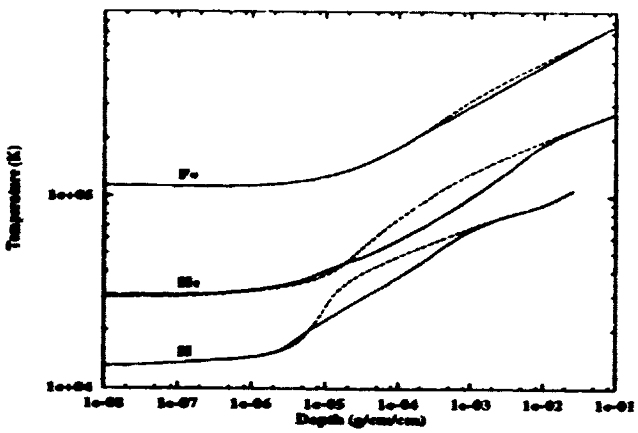

Fig. 1. **Temperature profiles with and without allowance for convection (solid and dashed curves, respectively) for H, He and Fe photospheres ($T_{eff} = 1.8 \times 10^4$, 4.1×10^4 and 1.4×10^5 K, respectively).**

The convective transfer affects not only the structure of photosphere but also the spectra of the NS thermal radiation (Fig. 2) because the temperature profiles are changed in the layers where the radiation escapes from. In particular, convection substantially (up to two orders of magnitide) lowers the flux from H and He photospheres at photon energies above the main photoionization edges, so that the high-energy spectral tails become softer. The spectra remain the same at low and very high energies since both shallow and very deep layers are not affected by convection. In the case of Fe composition, the convective zone lies so deep that only a high-energy tail ($E \gtrsim 0.3$ keV) is affected. The effect of convection on the spectra disappears with increasing effective temperature (*e. g.*, at $T_{eff} > 3 \times 10^4$ K for H, at $T_{eff} > 5 \times 10^4$ K for He and at $T_{eff} > 3 \times 10^5$ K for Fe photospheres).

The presented results correspond to the convective efficiency $l/H = 1$. Acceptable values of this parameter can vary from 0.3 to 2.5. Bergeron *et al.* (1992) showed that higher efficiency enhances convection and smoothes the spectra of white dwarfs. The same effect can be expected in the NS photospheres and, consequently, the convection

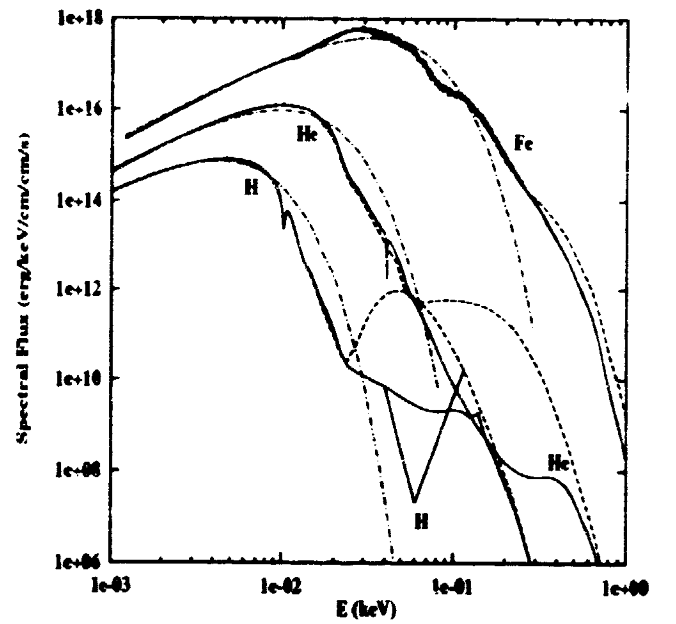

Fig. 2. **Spectra of outgoing radiation corresponding to the temperature profiles in Fig. 1. Dash-dotted curves are the blackbody spectra $\pi B(T_{eff})$.**

there may develop at higher effective temperatures than in the models presented. Hence, radiation from convective NS photospheres may be detected by ROSAT.

Convection in NS photospheres is important because it can mix the material in convective zones, bringing heavier elements from bottom to surface layers which would otherwise contain only light elements due to gravitational stratification. Our calculations show that this may happen in cold NSs with $T_{eff} \lesssim (3-5) \times 10^4$ K, whereas radiating layers of hotter NSs can be expected to consist mainly of hydrogen and helium. Since the presence of convection softens the high-energy tails of the spectra, this effect should be taken into account for the proper interpretation of EUV/soft-X-ray observations of thermal radiation from NSs.

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